

GA BASED OPTIMAL POWER FLOW SOLUTIONS

Thesis submitted in partial fulfillment of the requirements for the award of degree of

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in
Power Systems & Electric Drives**



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Certificate

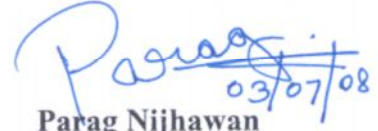
I hereby certify that the work which is being presented in the thesis entitled, “**GA Based Optimal Power Flow Solutions**”, in partial fulfillment of the requirements for the award of degree of Master of Engineering in *Power Systems & Electric Drives* submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Mr. Parag Nijhawan, Sr. Lecturer, EIED.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.



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This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.



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ABSTRACT

The optimal power flow (OPF) is a non-linear programming and highly constrained optimization problem. The objective is to present solution of optimal power flow problem of large transmission systems via a simple genetic algorithm. The main objective is to minimize the fuel cost and keep the power outputs of generators; bus voltages, shunt capacitors/reactors and transformers tap setting in their secure limits. The OPF has been usually considered as the minimization of an objective function representing the generation cost and/or the transmission loss.

Even though, excellent advancements have been made in classical methods, they suffer from disadvantages because of the extremely limited capability to solve real-world large-scale power system problems. They are weak in handling qualitative constraints. The major advantage of the GA is that it is relatively versatile for handling various qualitative constraints. It can find multiple optimal solutions in single simulation run. So they are quite suitable in solving multi-objective optimization problems.

OPF with reactive power compensation is also investigated in this work. The compensating device investigated in this study is shunt capacitor. Shunt capacitor is installed to provide capacitive reactive compensation/ power factor correction. Shunt capacitors are used to improve the quality of the electrical supply and the efficient operation of the power system. Also flat voltage profile on the system can significantly reduce line losses. Shunt capacitor are relatively inexpensive and can be easily installed anywhere on the network between any of the bus and the ground. The IEEE 30-bus system is investigated in this work.

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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

The increasing demand for an OPF tool for assessing state and recommended control actions for off-line and on-line studies has been on the increase since the first OPF paper was presented in the 60's. The lack of uniformity in usage and definition has also been a source of challenge to developers or users in OPF. The increasing need for OPF to solve problems of today's deregulated industry, and the unsolved problems in the vertically integrated industry has caused the working group on operating economics, through task force, challenges to OPF to evaluate the capabilities of existing OPF, in terms of their abilities. OPF has enjoyed the renewed interest in a variety of formulations, through the use of advanced optimized techniques such as, Genetic Algorithms, Interior Point methods, simulated annealing method, decomposition and Newton's method, and their contributions have been significant. Several production grade software suites with a family of applications have been in the market place and various industry and research archives. In spite of all the investment and work on OPF, the question is that as a real time control application how well the future OPF provide local or global control measures to support the impact of critical contingencies, which threaten system voltage and angle stability limits. Future OPF has to address the operation and planning environment in providing new generation facilities, unbundled transmission services and other resource allocations.

Typical examples of OPF applications are:

- Voltage Instability, Maximum transfers (V-P Curve Approach) or minimum compensation requirements (Q-V Curve Approach) to attain voltage stability are obtained in a single solution. Other constraints such as voltage and/or thermal limitations can be added.
- Reactive power compensation using capacitors, reactors or Flexible AC Transmission Systems (FACTS). OPF will likely be used to "dispatch" the

transmission network (e.g., series and shunt compensation) to overcome post disturbance thermal and voltage violations.

- Economic dispatch, subject to: thermal constraints, voltage constraints, interface constraints (e.g., stability) and spinning reserve constraints. From this dispatch, marginal costs and transmission bottlenecks are easily identified.

The work presented in this thesis utilizes an optimal power flow program, OPF, as the tool for solving the problems. The OPF is a natural choice for addressing these concerns because it is basically an optimal control problem. The OPF utilizes all control variables to help minimize the costs of the power system operation. It also yields valuable economic information and insight into the power system. In these ways, the OPF very adeptly addresses both the control and economic problems. After formulating the OPF problem, results are obtained by using genetic algorithm. Programming work is carried out in Matlab.

1.2 LITERATURE REVIEW

The Optimal power flow module is an intelligent load flow that employs techniques to automatically adjust the power system control settings while simultaneously solving the load flows and optimizing operating conditions with specific constraints. Reactive power compensation (RPC) is an important issue in electric power systems, involving operational, economical and quality of service aspects. Consumer loads (residential, industrial, service sector, etc.) impose active and reactive power demand, depending on their characteristics. Active power must be converted into “useful” energy, such as light or heat. Reactive power must be compensated to guarantee an efficient delivery of active power to loads, thus releasing system capacity, reducing system losses, and improving system power factor [1]. Genetic Algorithm (GA) approach is used for solving RPC problem including the line flow constraint.

The optimal power flow problem has been discussed since its introduction by Carpentier in 1962 [2]. Because the OPF is a very large, non-linear mathematical programming problem, it has taken decades to develop efficient algorithms for its

solution. Many different mathematical techniques have been employed for its solution [3].

The primary goal of a generic OPF is to minimize the costs of meeting the load demand for a power system while maintaining the security of the system. From the viewpoint of an OPF, the maintenance of system security requires keeping each device in the power system within its desired operation range at steady-state. This will include maximum and minimum outputs for generators, maximum MVA flows on transmission lines and transformers, as well as keeping system bus voltages within specified ranges [4].

As OPF only addresses steady-state operation of the power system so to achieve these goals, the OPF will perform all the steady-state control functions of the power system. These functions may include generator control and transmission system control. For generators, the OPF will control generator MW outputs as well as generator voltage. For the transmission system, the OPF may control the tap ratio or phase shift angle for variable transformers, switched shunt control, and all other flexible ac transmission system (FACTS) devices.

A secondary goal of an OPF is the determination of system marginal cost data. This marginal cost data can aid in the pricing of MW transactions as well as the pricing auxiliary services such as voltage support through MVAR support.

The solution of the OPF, while difficult, has many great advantages over the classical economic dispatch [3] of a power system. The OPF is capable of performing all of the control functions necessary for the power system. While the economic dispatch of a power system does control generator MW output, the OPF controls transformer tap ratios and phase shift angles as well. The OPF also is able to monitor system security issues including line overloads and low or high voltage problems. If any security problems occur, the OPF will modify its controls to fix them, i.e., remove a transmission line overload [5-13].

To solve OPF problem ‘Ant Colony Optimization Method’ (ACO) is used by Tarek Bouktir and Linda Slimani in conjunction with GA [16]. ACO is characterized by the use of a (parameterized) probabilistic model that is used to generate solutions to the problem under consideration. The probabilistic model is called the pheromone model. In

this paper, the application of the ant colony optimization algorithms in the Optimal Power Flow (OPF) on the Algerian Electrical Network is showed. The ACO is more likely to converge toward the global solution because it, simultaneously, evaluates many points in the parameter space. It does not need to assume that the search space is differentiable or continuous. To accelerate the processes of ACO-OPF, the controllable variables are decomposed to active constraints that effect directly the cost function are included in the ACO process and passive constraints which are updating using a conventional load flow program, only, one time after the convergence on the ACO-OPF[14-16].

Different classical techniques have been also employed to solve the OPF problem e.g. Lambda iteration method, Gradient method, Newton's method [17], Linear programming method [18], Interior point method [19]. Lambda iteration method also called the equal incremental cost criterion (EICC) method has its roots in the common method of economic dispatch used since the 1930s [3]. In [20] James Daniel Weber solved the OPF problem using Newton's Method. In this marginal cost data are determined as a by product of the solution technique. Newton method and gradient method suffers from the difficulty in handling the inequality constraints. To apply LP, input output function is to be expressed as a set of linear functions which may lead to loss of accuracy. Moreover they are not guaranteed to converge to the global optimum of the general non-convex OPF problem.

However, all of these methods suffer from three main problems. Firstly, they may not be able to provide the optimal solution and usually getting stuck at a local optimum [21]. Secondly, all these methods are based on the assumption of continuity and differentiability of the objective function, which is not true in a practical system. Finally, all these methods cannot be applied with discrete variables which are transformer taps. It seems that GA and EP (Evolutionary programming) are appropriate methods to solve this problem, which eliminates the above drawbacks.

The genetic algorithms are part of the evolutionary algorithms family, which are computational models, inspired in the Nature. Genetic algorithms are powerful stochastic search algorithms based on the mechanism of natural selection and natural genetics. GAs works with a population of binary string, searching many peaks in parallel. By employing genetic operators, they exchange information between the peaks, hence reducing the

possibility of ending at a local optimum. GAs are more flexible than most search methods because they require only information concerning the quality of the solution produced by each parameter set (objective function values) and not like other optimization methods which require derivative information, or worse yet, complete knowledge of the problem structure and parameters[24].

There are some difference between GA's and traditional searching algorithms [24-26]. They are summarized as follows:

- The algorithms work with a population of string, searching many peaks in parallel, as opposed to a single point.
- GAs work directly with strings of characters representing the parameters set not the parameters themselves.
- GAs use probabilistic transition rules instead of deterministic rules.
- GAs use objective function information instead of derivatives or others auxiliary knowledge.
- GAs has the potential to find solutions in many different areas of the search space simultaneously [23-31].

Genetic programming is a domain-independent problem-solving approach in which computer programs are evolved to solve, or approximately solve, problems. Genetic programming is based on the Darwinian principle of reproduction and survival of the fittest and analogs of naturally occurring genetic operations such as *crossover* and *mutation* [32]. John Holland's pioneering *Adaptation in Natural and Artificial Systems* (1975) described how an analog of the evolutionary process can be applied to solving mathematical problems and engineering optimization problems using what is now called the *genetic algorithm* (GA). The genetic algorithm attempts to find a good (or best) solution to the problem by genetically breeding a population of individuals over a series of generations. In the genetic algorithm, each *individual* in the population represents a candidate solution to the given problem. The *genetic algorithm* (GA) transforms a *population* (set) of individuals, each with an associated *fitness* value, into a new *generation* of the population using reproduction, crossover, and mutation.

Crossover is the primary genetic operator, which promotes the exploration of new regions in the search space. Mutation is a secondary operator and prevents the premature

stopping of the algorithm in a local solution. The mutation operator is defined by a random bit value change in a chosen string with a low probability of such change. The mutation adds a random search character to the genetic algorithm, and it is necessary to avoid that, after some generations. Reproduction is based on the principle of survival of the better fitness. It is an operator that obtains a fixed number of copies of solutions according to their fitness value. If the score increases, then the number of copies increases too. A score value is associated to a given solution according to its distance of the optimal solution (closer distances to the optimal solution mean higher scores) [33-37]. In paper [38] Y. J. Cao and Q. H. Wu used MATLAB in implementing the genetic operators: crossover, mutation, and selection.

A GA solution to the OPF problem has been applied to small and medium size power systems. The main advantage of the GA solution to the OPF problem is its modeling flexibility, discrete control variables, and complex, nonlinear constraints can be easily modeled. Another advantage is that it can be easily coded to work on parallel computers. The main disadvantage of GA's is that they are stochastic algorithms and the solution they provide to the OPF problem is not guaranteed to be the optimum. Another disadvantage is that the execution time and the quality of the provided solution deteriorate with the increase of the chromosome length, i.e., the OPF problem size. The applicability of the GA solution to large-scale OPF problems of systems with several thousands of nodes, utilizing the strength of parallel computers, has yet to be demonstrated [39].

Reactive power compensation is an important issue in electric power systems, involving operational, economical and quality of service aspects. Consumer loads (residential, industrial, service sector, etc.) impose active and reactive power demand, depending on their characteristics. Active power is converted into "useful" energy, such as light or heat. Reactive power must be compensated to guarantee an efficient delivery of active power to loads, thus releasing system capacity, reducing system losses, and improving system power factor and bus voltage profile. The achievement of these aims depends on the sizing and allocation of shunt capacitors (sources of reactive power) [40-43].

The purpose of Reactive Power compensation is mainly to improve the voltage profile in the system and to minimize the real power transmission loss while satisfying the unit and system constraints [1]. This goal is achieved by proper adjustment of reactive power control variables like Generator bus voltage magnitudes (V_{gi}), transformer tap settings (t_i), reactive power generation of the capacitor bank (Q_{ci}). The problem of reactive power compensation involves to determine the sizes for shunt capacitors (sources of reactive power) to be installed, to reduce losses and improve the voltage profile [44-48].

Reactive power is a very important ancillary service that ensures the power system to operate safely and stably. In the power market, independent system operator (ISO) must satisfy the demand of reactive power loads and supports the voltage of power system by controlling reactive power and voltage to ensure the security and stability of system. Generally, the reactive power and voltage are controlled by regulating the output of reactive power resources and the ratio of transformers. Reactive power resources include generators and all kinds of reactive compensation devices, such as synchronous condenser, shunt capacitor and SVC [49][50].

1.3 SCOPE OF WORK

This thesis will commence with an overview of the problems encountered with OPF and reactive power compensation. The primary goal of a OPF problem is to minimize the costs of meeting the load demand for a power system while maintaining the security of the system. This is followed by literature review that covers the research of useful background theories. From the understanding of theories, a description of methodologies will be discussed. The result from performed studies and Matlab programming will also be discussed in detail. Finally the thesis will end with a conclusion of the thesis and recommendations for future work in this area of research.

1.4 ORGANIZATION OF THESIS

In the thesis, the OPF problem is solved by using genetic algorithm as its solution algorithm. It will tackle all of the goals set forth for an OPF including the control of switched shunt capacitor.

The remainder of this thesis will discuss the development of the OPF. Chapter 2 of this thesis will discuss the theory of the optimal power flow and lay a framework for the mathematics and engineering behind the OPF computer source code. Chapter 3 will discuss Genetic algorithm to solve an OPF which achieves solution in a rapid manner. Chapter 4 will include reactive power compensation method in OPF problem. Chapter 5 will show the results and its discussion. Finally, Chapter 6 will conclude with a summary, scope of future work and several improvements which would aid in creating a truly useful OPF.

CHAPTER 2

OPTIMAL POWER FLOW

2.1 INTRODUCTION

Optimal power flow (OPF) has been widely used in power system operation and planning. The Optimal power flow module is an intelligent load flow that employs techniques to automatically adjust the power system control settings while simultaneously solving the load flows and optimizing operating conditions with specific constraints. Optimal power flow (OPF) is a static nonlinear programming problem which optimizes a certain objective function while satisfying a set of physical and operational constraints imposed by equipment limitations and security requirements. In general, OPF problem is a large dimension nonlinear and highly constrained optimization problem. [51-54].

So the objective is to minimize the fuel cost and keep the power outputs of generators, bus voltages, shunt capacitors/reactors and transformers tap setting in their secure limits. The OPF has been usually considered as the minimization of an objective function representing the generation cost and/or the transmission loss. The constraints involved are the physical laws governing the power generation-transmission systems and the operating limitations of the equipment.

2.2 GOALS OF OPF

Before beginning the creation of an OPF, it is useful to consider the goals that the OPF will need to accomplish. The primary goal of a generic OPF is to minimize the costs of meeting the load demand for a power system while maintaining the security of the system. The costs associated with the power systems may depend on the situation but in general they can be attributed to the cost of generating power (megawatts) of each generator. From the viewpoint of an OPF, the maintenance of system security requires keeping each device in the power system within its desired operation range at steady state. This will include maximum and minimum output for generators, maximum MVA flows on transmission lines and transformers, as well as keeping the system bus voltages

within the specified ranges. It should be noted that the OPF only addresses steady state operation of the power system [1][2].

The standard OPF problem can be written in the following form

Min. $F(x)$

Subject to: $h(x)=0$

and $g(x) \geq 0$

where $F(x)$ is the objective function, $h(x)$ is the equality constraints and $g(x)$ is the inequality constraints. And x is the vector of control variables (like generated active and reactive power, generation bus voltage magnitudes, transformer taps etc)

The essence of the optimal power flow problem resides in reducing the objective function and simultaneously satisfying the load flow equations (equality constraints) without violating the inequality constraints [20-22].

2.3 OBJECTIVE FUNCTION

The most commonly used objective in the OPF problem formulation is the minimization of total cost of real power generation. The individual costs of each generating unit are assumed to be a function, only of active power generation and are represented by quadratic curves of second order. The objective function of the entire power system can then be written as the sum of the quadratic cost model at each generator.

$$F_i = a_i P_{g_i}^2 + b_i P_{g_i} + c_i$$

where $i = 1, 2, 3, \dots, n_g$.

where n_g is number of generators including the slack bus, P_{g_i} is the generated active power at bus i .

a_i, b_i, c_i are the unit cost curve for i^{th} generator

The cost is optimized with the following constraints.

2.3.1 Types of Equality Constraints

While minimizing the cost function, it is necessary to make sure that the generation still supplies the load demands (P_d) plus losses in transmission lines [24].

Usually the power flow equations are used as equality constraints:

- The power flow equation of the network

$$g(V, \phi) = 0$$

$$\text{where } g(V, \phi) = \begin{cases} P_i(V, \phi) - P_i^{\text{net}} \\ Q_i(V, \phi) - Q_i^{\text{net}} \\ P_m(V, \phi) - P_m^{\text{net}} \end{cases}$$

← For each PQ bus i
 ← For each PV bus m, not including the ref. bus

where

P_i and Q_i are calculated real and reactive power for PQ bus i respectively.

P_i^{net} and Q_i^{net} are specified real and reactive power for PQ bus i respectively.

P_m and P_m^{net} are calculated and specified real power for PV bus m respectively.

V and ϕ are voltage magnitude and phase angle at different buses respectively.

2.3.2 Types of Inequality Constraints

The inequality constraints of the OPF reflect the limits on physical device in the power systems as well as the limits created to ensure system security. The most usual types of inequality constraints are upper bus voltage limits at generations at load buses, lower bus voltage limits at some generators, maximum line loading limits and limits on tap settings. The inequality constraints on problem includes:

- The inequality constraint on real power generation at bus i

$$P_{g_i}^{\min} \leq P_{g_i} \leq P_{g_i}^{\max}$$

where $P_{g_i}^{\min}$ and $P_{g_i}^{\max}$ are resp. minimum and maximum values of real power generation allowed at generator bus i.

- The inequality constraint on reactive power generation Q_{g_i} at each PV bus.

$$Q_{g_i}^{\min} \leq Q_{g_i} \leq Q_{g_i}^{\max}$$

Where $Q_{g_i}^{\min}$ and $Q_{g_i}^{\max}$ are respectively minimum and maximum value of reactive power at PV bus i.

- The inequality constraint on voltage magnitude V of each PQ bus.

$$V_i^{\min} \leq V_i \leq V_i^{\max}$$

Where V_i^{\min} and V_i^{\max} are respectively minimum and maximum voltage at bus i.

- The inequality constraint on phase angle ϕ_i of voltage at all buses i.

$$\phi_i^{\min} \leq \phi_i \leq \phi_i^{\max}$$

Where ϕ_i^{\min} and ϕ_i^{\max} are respectively minimum and maximum phase angle at bus i.

- MVA flow limit on transmission line

$$MVA_{ij} \leq MVA_{ij}^{\max}$$

where MVA_{ij}^{\max} is the maximum rating of transmission line connecting bus i and j.

2.4 PROBLEMS IN OPF

OPF was introduced in 1968, several methods have been employed to solve this problem, eg Gradient base [2], linear programming method [3] and quadratic programming [4]. But, all of these methods suffer from three main problems. Firstly, they may not be able to provide the optimal solution and usually getting stuck at a local optimum [5]. Secondly, all these methods are based on the assumption of continuity and differentiability of the objective function, which is not true in a practical system. Finally, all these methods cannot be applied with discrete variables which are transformer taps. It seems that GA is an appropriate method to solve this problem, which eliminates the above drawbacks [7][8][74].

3.1 INTRODUCTION

Many classical techniques [17-20], such as nonlinear programming (NLP), quadratic programming (QP) and linear programming (LP) are used for solving the OPF problem. The gradient based methods and Newton methods [20] suffer from the difficulty in handling inequality constraints. Moreover, these NLP and QP methods rely on convexity to obtain the global optimum solution and as such are forced to simplify relationships in order to ensure convexity. To apply linear programming [10], input–output function is to be expressed as a set of linear functions, which may lead to loss of accuracy. Moreover they are not guaranteed to converge to the global optimum of the general non-convex OPF problem. These days, genetic algorithm (GA) [53],[57-60] and evolutionary programming techniques (EP) [61-64] are used to overcome the above-mentioned difficulties of classical methods.

The genetic algorithms are part of the evolutionary algorithms family, which are computational models, inspired in the Nature. Genetic algorithms are powerful stochastic search algorithms based on the mechanism of natural selection and natural genetics. GA works with a population of binary string, searching many peaks in parallel. By employing genetic operators, they exchange information between the peaks, hence reducing the possibility of ending at a local optimum. GA's are more flexible than most search methods because they require only information concerning the quality of the solution produced by each parameter set (objective function values) and not like many optimization methods which require derivative information, or worse yet, complete knowledge of the problem structure and parameters.

There are some difference between GAs and traditional searching algorithms [72][73]. They are summarized as follows:

- The algorithm works with a population of string, searching many peaks in parallel, as opposed to a single point.

- GA works directly with strings of characters representing the parameters set not the parameters themselves.
- GA uses probabilistic transition rules and not the deterministic rules.
- GA uses objective function information instead of derivatives or other auxiliary knowledge.
- GA has the potential to find solutions in many different areas of the search space simultaneously.

3.2 GENETIC ALGORITHM

The GA begins, like any other optimization algorithm, by defining the optimization variables, the cost function, and the cost. It ends like other optimization algorithms too, by testing for convergence. In between, however, this algorithm is quite different. A path through the components of the GA is shown in Figure 3.2.1

General method of coding in genetic algorithm is binary and decimal system. Main merit of binary system is that it is convenient to realize crossover and mutation manipulation and so on and has good searching ability, but towards optimized problem with high precision and continuous function, the length of coding cluster is hard to decide, because too short length is difficult to satisfy the demand of precision and too long length will reduce the velocity and capability of algorithm.

We use genetic algorithm because the features of Genetic algorithm are different from other search techniques in the several aspects. First the algorithm is a multipath that searches many peaks in parallel and hence reducing the possibility of local minimum trapping. Secondly, GA works with a coding of parameters instead of the parameters themselves. The coding of parameter will help the genetic operator to evolve the current state into the next state with minimum computations. Thirdly, GA evaluates the fitness of each string to guide its search instead of the optimization function. The genetic algorithm only needs to evaluate objective function (fitness) to guide its search. Finally, GA explores the search space where the probability of finding improved performance is high.

Some members of new population undergo genetic operations to form new solutions. The three commonly used operations are reproduction, crossover and mutation.

With the above description, a simple genetic algorithm is given as follow:

1. Generate randomly a population of binary string
2. Calculate the fitness for each string in the population
3. Create offspring strings through reproduction, crossover and mutation operation.
4. Evaluate the new strings and calculate the fitness for each string (chromosome).
5. If the search goal is achieved, or an allowable generation is attained, return the best chromosome as the solution; otherwise go to step 3.

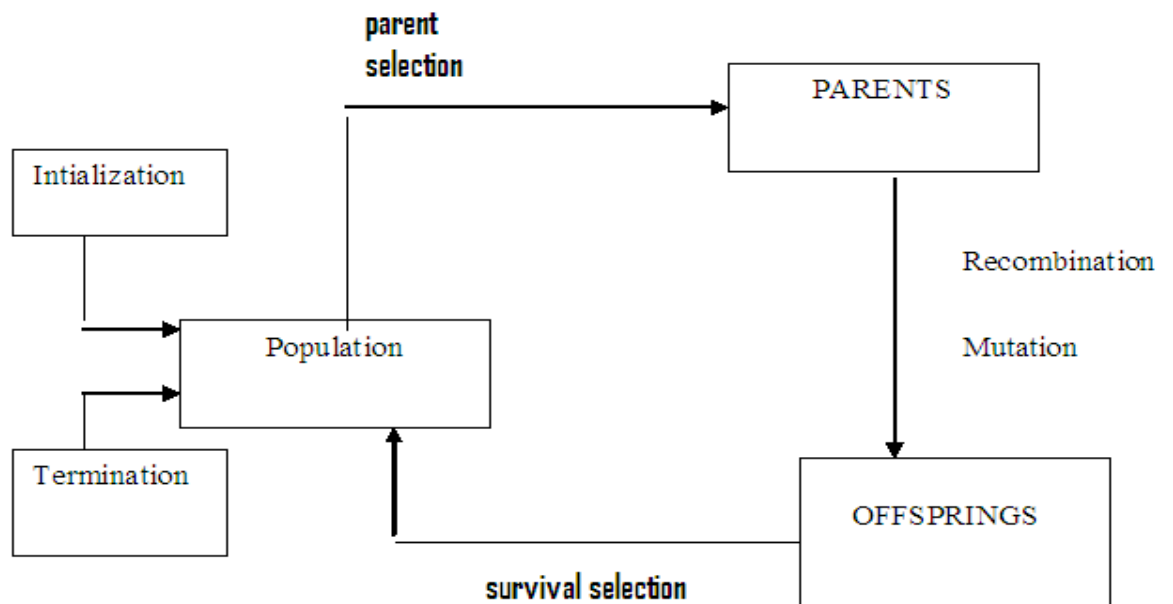


Figure 3.1: Standard Procedure of a Genetic Algorithm.

Various components of GA are described below:

3.2.1 Reproduction

The reproduction operator is a probabilistic selection in which strings are selected so as to produce offspring based on their fitness value. There are number of selection

methods such as fitness proportionate selection, ranking and tournament selection. Tournament selection is used in this work. In tournament selection, ‘n’ individuals are selected randomly from the population, and the best of the ‘n’ is inserted into the new population for further genetic processing. This procedure is repeated until the mating pool is filled [10].

3.2.2 Crossover Operation

Crossover is the primary genetic operator, which promotes the exploration of new regions in the search space. Crossover is an important random operator in GA and the function of the crossover operator is to generate new or ‘child’ chromosomes from two ‘parent’ chromosomes by combining the information extracted from the parents. The method of crossover used in GA is the one-point crossover as shown in figure 3.2.2. By this method, for a chromosome of a length l , a random number c between 1 and l is first generated. The first child chromosome is formed by appending the last $l-c$ elements of the first parent chromosome to the first c elements of the second parent chromosome. The second child chromosome is formed by appending the last $l-c$ elements of the second parent chromosome to the first c elements of the first parent chromosome. Typically, the probability for crossover ranges from 0.6 to 0.95[51-53].

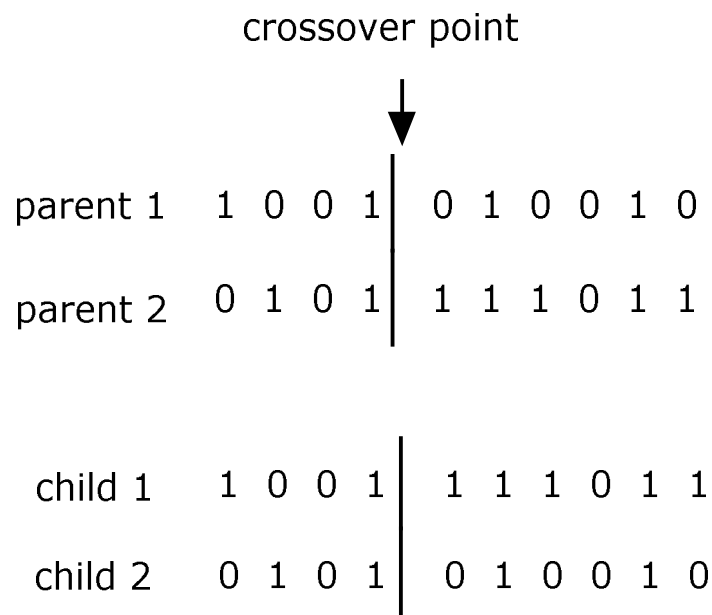


Figure 3.2: Crossover Operation

3.2.3 Mutation

The final genetic operator in the algorithm is mutation. The mutation operator is used to inject new genetic materials into the population as shown in figure below



Figure 3.3: Mutation Operation

Mutation prevents the premature stopping of the algorithm in a local solution. The mutation operator is defined by a random bit value change in a chosen string with a low probability of such change. The mutation adds a random search character to the genetic algorithm, and it is necessary to avoid that, after some generations, all possible solutions were very similar ones. Bit wise mutation is performed here, which switches a few randomly chosen bits from 1 to 0 (or) 0 to 1 with a small probability (P_m). After mutation, the new generation is complete and the procedure begins again with the fitness evaluation of the population [58-60].

All strings and bits have the same probability of mutation. For example, in the string 1101010010, if the mutation affects to time bit number eight, the string obtained is 1101010110 and the value of P_{g_2} change from 0.85 p.u to 0.75 p.u.

3.4 GENETIC ALGORITHM IN OPTIMAL POWER FLOW

It can be seen that the generalized objective function F is a non-linear, the number of the equality and inequality constraints increase with the size of the power distribution systems. Applications of a conventional optimization technique such as the gradient-based algorithms to a large power distribution system with a very non-linear objective functions and great number of constraints are not good enough to solve this problem,

because it depend on the existence of the first and the second derivatives of the objective function. So to avoid such limitations we use GA [4][62][63][65][71].

A simple Genetic Algorithm is an iterative procedure, which maintains a constant size population P of candidate solutions. During each iteration step (generation) three genetic operators (reproduction, crossover, and mutation) are performing to generate new populations (offspring), and the chromosomes of the new populations are evaluated via the value of the fitness witch is related to cost function. Based on these genetic operators and the evaluations, the better new populations of candidate solution are formed [6-9].

3.5 ALGORITHM

Step-by-Step Algorithm for Genetic Algorithm Based OPF

Step1. Read the database for the generator data, bus data, capacitor/reactor data, transformer data and transmission line data.

Step2. Assume suitably population size (pop size), maximum number of generations or populations (gen_max).

Step3. Set valid number of population counter. pop_vn=0.

Step4. Randomly generate the chromosomes.

Step5. Run power flow using the Newton-Rapson method for each set of generating patterns P_{g_i} corresponding to a particular generation and after that determine, slack bus generation, bus voltage magnitudes and phase angles at all the buses. Also calculate power flow in each transmission line of the system.

Step6. Check the following constraints,

- Check the voltage magnitude violation

$$V_i^{\min} \leq V \leq V_i^{\max}$$

- Check the bus voltage phase angle

$$\varnothing_i^{\min} \leq \varnothing_i \leq \varnothing_i^{\max}$$

- Check the MVA flows violation

$$MVA_{ij}^{\min} \leq MVA_{ij}^{\max}$$

- Check reactive power limits at all generator buses

If any of the above limits is violated, go to step 4.

Step7. If all the above constraints are satisfied, increment pop_vn by 1. If pop_vn less than or equal to pop_size, go to step 4, otherwise go to next step.

Step8. Calculate and then store the total cost of generation corresponding to each valid generation pattern of chromosome

Step9. Find and store minimum cost among all valid individual parents and corresponding generation pattern.

Step11: Check if random no. $r_i < cr$ (crossover rate) for $i=1$ to pop_size, select i^{th} chromosome. Apply the crossover operator to that individual.

Step12. Run power flow using Newton-Raphson method for each set of new generating patterns and hence determine, slack bus generation, bus voltage magnitudes and phase angles at all the buses. Also calculate power flow in each transmission line of the system.

Step13. Check system constraints as mentioned in step 6.

Step14: If all the constraints are satisfied, the individual of the new population becomes valid otherwise it becomes invalid.

Step15. Apply the mutation operator to the calculated generation patterns.

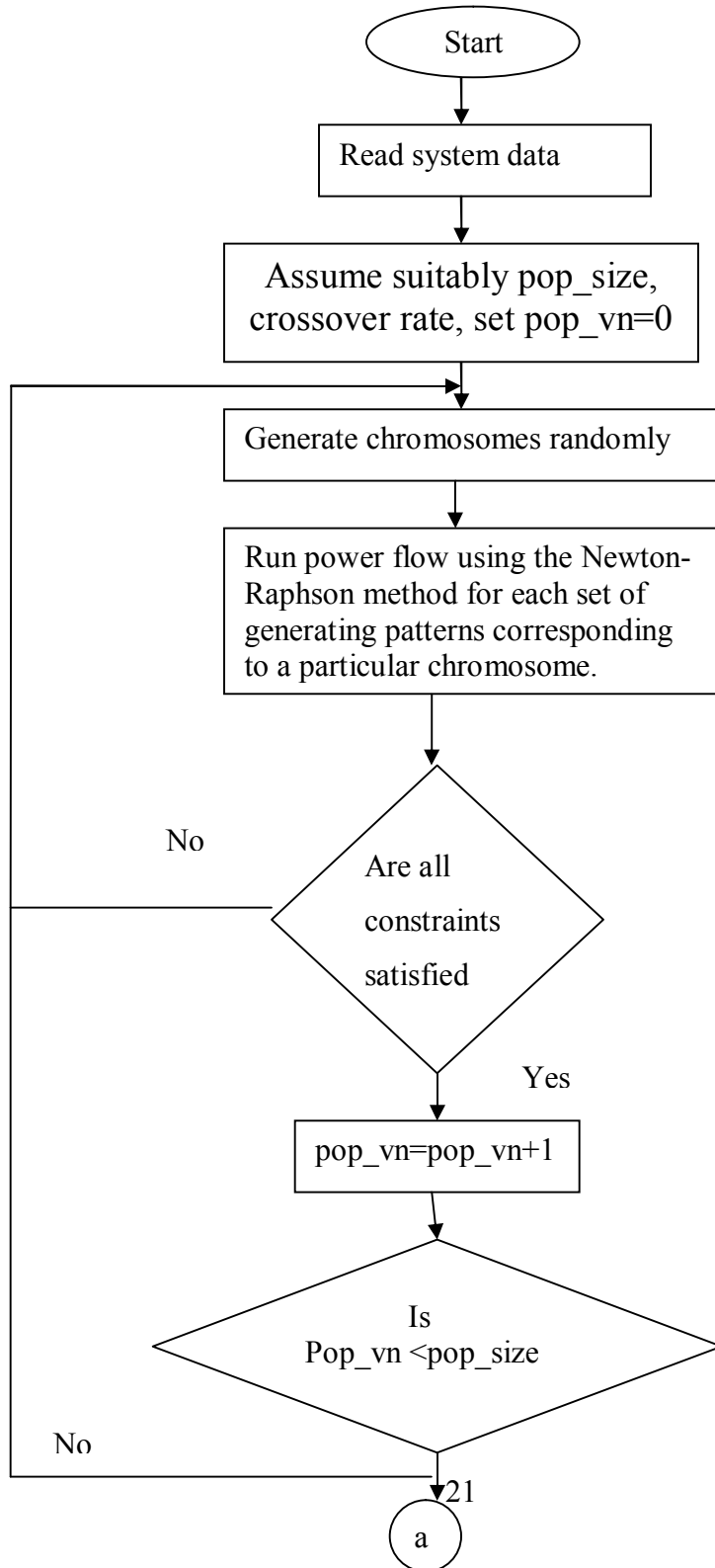
Step16. Run power flow using the Newton raphson and check all the constraints as mentioned in step 6.

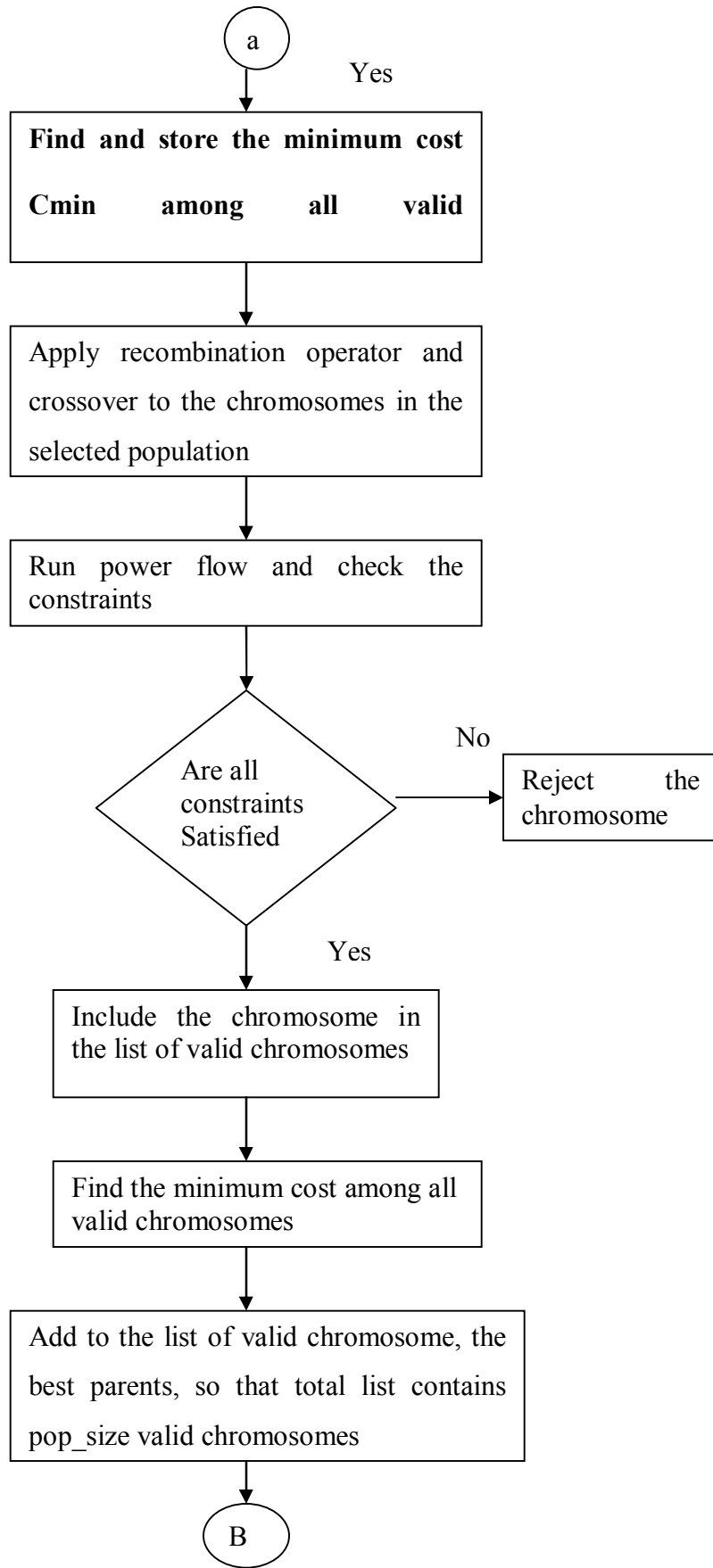
Step17 If all the constraints are satisfied go to next step otherwise go to step 4.

Step18. Calculate the total cost of all valid patterns.

Step19. Find the optimum solution among all population groups.

3.6 FLOWCHART





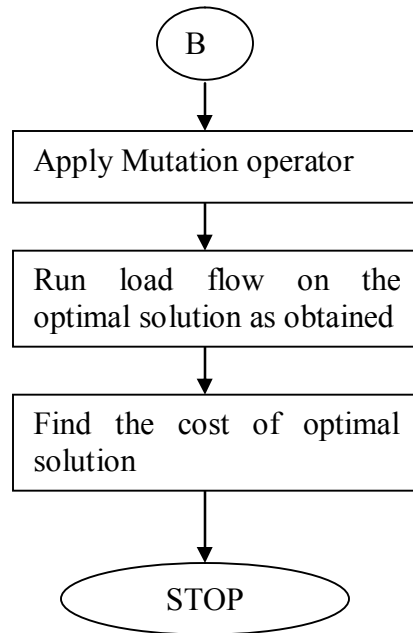


Figure 3.4 Flowchart

REACTIVE POWER COMPENSATION

4.1 INTRODUCTION

Shortage of reactive power support in power system increases the vulnerability of system to voltage instability and voltage collapse conditions. Shortage of reactive power occurs at generation outages, transmission contingencies or increase in power transfer levels. During the daily operation, power systems may experience both over-voltage and under-voltage violations that can be overcome by voltage or Var control [1]. Through controlling the production, adsorption, and flow of reactive power at all levels in the system, voltage/Var control can maintain the voltage profile within acceptable limit and reduce the transmission losses. Reactive power compensation, is therefore, very essential to maintain the reliability, quality and capacity of power delivery [43-44].

Thus compensation by shunt method means change of reactive power at a point of a network by means of reactor, capacitors or synchronous compensators connected to the network [50].

4.2 REACTIVE POWER SOURCES & THEIR CONTROL DEVICES

The controllable reactive power sources include generators, shunt reactors, shunt capacitors and On Load Tap Changers of transformers (OLTC). Generators can generate or absorb reactive power depending on the excitation. When overexcited they supply the reactive power, and when under excited they absorb reactive power. The automatic voltage regulators of generators can continually adjust the excitation [1].

Reactors, shunt capacitors, and OLTC are traditionally switched on/off through circuit breakers on command from the operator. Since the early eighties, advances in Flexible AC Transmission Systems (FACTS) controllers in power systems have led to their application to improve voltage profiles of power networks. The most frequently used devices are: Reactive Power Controller (RPC) and Static Var Compensator (SVC) [67].

Shunt reactors with their compensating effect on the capacitive generation of line offer a technically and economically sound means of controlling the undesirable over voltage.

Shunt capacitive compensation is an alternative means of increasing the transmission capacity and also reducing the losses. One advantage claimed by shunt capacitive compensation is that it is possible to maintain nodal voltage at nominal value through injection of reactive power along the line. Another advantage is its capability to increase the steady state stability and improve damping when use in conjunction with static Var controllers [66-67]. Capacitors are connected either directly to bus bar and are disposed along the route to minimize the losses and voltage drops [46-49].

Given the receiving end voltage (V_r) , sending end voltage(V_s) ,real power(P_r) and reactive power(Q_r) at the receiving end of the line the required Capacitor Mvar at the receiving end for a specified load can be computed. The Mvar value of the capacitor can be obtained by definition given below [68]:

$$Mvar = V^2 / X_c$$

$$\text{where } X_c = 1/\omega c$$

4.3 SHUNT CAPACITOR

Shunt capacitors are relatively inexpensive to install and maintain. Installing shunt capacitors in the load area or at the point that they are needed will increase the voltage stability. However, shunt capacitors have the problem of poor voltage regulation and, beyond a certain level of compensation; a stable operating point is unattainable. Furthermore, the reactive power delivered by the shunt capacitor is proportional to the square of the terminal voltage. Shunt capacitors are used to improve the quality of the electrical supply and the efficient operation of the power system. Also flat voltage profile on the system can significantly reduce line losses. Shunt capacitor are relatively inexpensive and can be easily installed anywhere on the network [50]. Figure below shows the electrical system model.

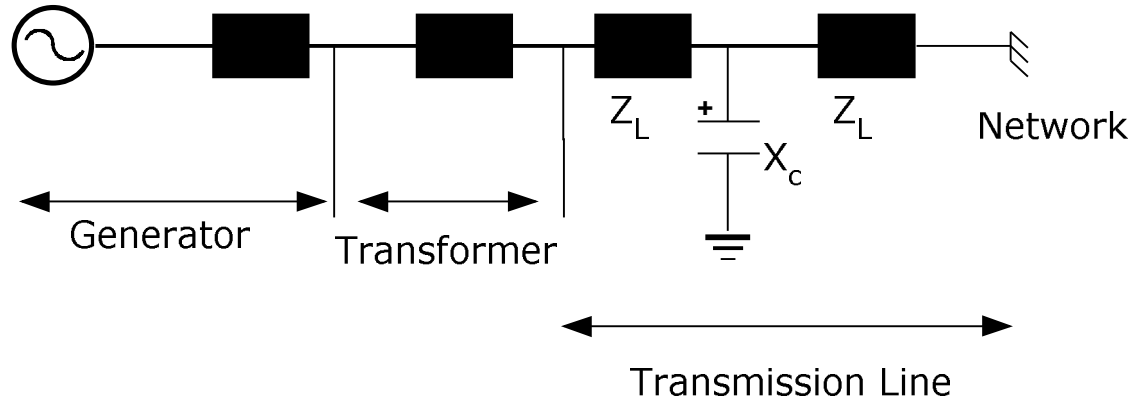


Figure 4.1: Electrical System Model

Shunt capacitor are mainly installed to provide capacitive reactive compensation/ power factor correction. The use of shunt capacitors has increased because they are relatively inexpensive, easy and quick to install and can be deployed virtually anywhere in the network. Its installation has other beneficial effects on the system such as: improvement of the voltage at the load, better voltage regulation (if they were adequately designed), reduction of losses and reduction or postponement of investments in transmission. The main disadvantage of it is that its reactive power output is proportional to the square of the voltage and consequently when the voltage is low and the system need them most, they are the least efficient [69-70].

CHAPTER 5

RESULTS AND DISCUSSION

5.1 GA BASED OPF RESULTS

The GA based optimization method is applied to the IEEE 30 bus system. Its bus data, line data and cost coefficients are given in Appendix A. only generator real power is taken as control variable. GA is used for various types of optimization problems.

After running load flow, the generation values of different generators are:

Table 5.1: Simple Load Flow Results

Generator	MW
1	229.571
2	20.00
3	15.00
4	10.00
5	10.00
6	12.00

Total losses are 13.221 MW and 18.265 Mvar

Total generation is 296.5711 MW

Total cost for dispatch is 833.27 \$/hr

Optimal generations are:

Table 5.2: Load Flow after Implementing GA

Generator	MW
1	189.728
2	45.822
3	17.333
4	14.706
5	13.686
6	12.769

Total generation is 294.105 MW
 Total losses are 10.738 MW and 9.325 Mvar

Total cost for this dispatch is 805.4112 \$/hr

Genetic algorithm based optimal power flow method is successfully implemented on IEEE 30 bus test system. In this firstly we generate a random number and by using this random number load flow program is run. From this we get different values of generations for each generator. On this crossover and mutation processes are applied and optimal cost is obtained while maintaining constraints within limits.

5.2 REACTIVE POWER COMPENSATION RESULTS

5.3 Results before Compensation

Table 5.3

BUS NO.	LOSSES		VOLTAGE MAGNITUDE	MVAR BEFORE COMPENSATION
	MW	MVAR		
12	10.738	9.325	1.040	37.604

5.4 Results after Compensation

Table 5.4

BUS NO.	LOSSES		VOLTAGE MAGNITUDE	MVAR AFTER COMPENSATION
	MW	MVAR		
12	10.744	9.029	1.045	33.426

In this capacitor is incorporated in the network for reactive power compensation. Capacitor is connected in shunt with Bus no. 12. The value of Y_c used is 0.066 P.U. The total compensation is 4.178 P.U. The OPF solution with and without shunt compensation for the IEEE-30 bus system is given in Appendix B [74].

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

In the thesis an attempt has been made to review various optimization methods used to solve OPF problems. Even though, excellent advancements have been made in classical methods, they suffer with the following disadvantages: In most cases, mathematical formulations have to be simplified to get the solutions because of the extremely limited capability to solve real-world large-scale power system problems. They are weak in handling qualitative constraints. They have poor convergence, may get stuck at local optimum, they can find only a single optimized solution in a single simulation run, they become too slow if number of variables are large and they are computationally expensive for solution of a large system. Whereas, the major advantage of the GA is that it is relatively versatile for handling various qualitative constraints. It can find multiple optimal solutions in single simulation run. So they are quite suitable in solving multi-objective optimization problems. In most cases, GA can find the global optimum solution.

The advantages of GA methods are: It only uses the values of the objective function and less likely to get trapped at a local optimum. Higher computational time is its disadvantage. The more advantages of GA are adaptability to change, ability to generate good enough solutions and rapid convergence. GA is used to solve multi objective generation scheduling, optimal reactive power dispatch and to minimize total cost of power generation.

Application of Genetic algorithm approach to solve Optimal Power Flow problem with and without shunt compensation by incorporating shunt capacitor has been explored and tested. The results presented in thesis are obtained for IEEE - 30 bus test system.

6.2 SCOPE OF FUTURE WORK

The first objective that is the minimization of system costs, while maintaining system security, was accomplished through the implementation of Genetic algorithm to

the OPF problem. GA method has proven to be very adept at solving the OPF problem. And the second objective was the reactive power compensation, which is done by installing shunt capacitor. After many years, the shunt and series compensation schemes are still the best methods to improve on the transmission capability. The shunt and series configuration schemes have been extensively used for reactive power compensation.

One suggestion for future work in this area of study is to explore or investigate the use of FACTS (Flexible AC transmission systems) devices instead of shunt capacitor for the purpose of reactive power compensation (RPC).

The other suggestion is related to the determination of the optimum location of the different RPC schemes.

APPENDIX A

Table A-1: Line Data

S.no	Bus from	Bus to	R (P.U)	X (P.U)	$\frac{1}{2}(B)$ (P.U)	Tap ratio	MW flow limit
1	1	2	.01920	0.05750	.02640	1	1.3
2	1	3	.04520	0.18520	0.02040	1	1.3
3	2	4	.05700	0.17370	.01840	1	.65
4	3	4	.01320	0.03790	.00420	1	1.3
5	2	5	.04720	0.1830	0.02090	1	1.3
6	2	6	.05810	.17630	0.01870	1	.65
7	4	6	.01190	0.04140	0.00450	1	.9
8	5	7	.04600	.11600	0.01020	1	1.3
9	6	7	0.02670	0.08200	0.00850	1	1.3
10	6	8	0.01200	0.04200	0.00450	1	0.32
11	6	9	0.00000	0.20800	0.00000	1.01550	0.65000
12	6	10	0.00000	0.55600	0.00000	0.96290	0.32000
13	9	11	0.00000	0.20800	0.00000	1	0.65000
14	9	10	0.00000	0.11000	0.00000	1	0.65000
15	4	12	0.00000	0.25600	0.00000	1.01290	0.65000
16	12	13	0.00000	0.14000	0.00000	1	0.65000
17	12	14	0.12310	0.25590	0.00000	1	0.32000
18	12	15	0.06620	0.13040	0.00000	1	0.32000
19	12	16	0.09450	0.19870	0.00000	1	0.32000
20	14	15	0.22100	0.49970	0.00000	1	0.16000
21	16	17	0.08240	0.19320	0.00000	1	0.16000
22	15	18	0.10700	0.21850	0.00000	1	0.16000
23	18	19	0.06390	0.12920	0.00000	1	0.16000
24	19	20	0.03400	0.06800	0.00000	1	0.32000
25	10	20	0.09360	0.20900	0.00000	1	0.32000
26	10	17	0.03240	0.08450	0.00000	1	0.32000
27	10	21	0.03480	0.07490	0.00000	1	0.32000
28	10	22	0.07270	0.14990	0.00000	1	0.32000
29	21	22	0.01160	0.02360	0.00000	1	0.32000
30	15	23	0.10000	0.20200	0.00000	1	0.16000
31	22	24	0.11500	0.17900	0.00000	1	0.16000
32	23	24	0.13200	0.27000	0.00000	1	0.16000
33	24	25	0.18850	0.32920	0.00000	1	0.16000
34	25	26	0.25440	0.38000	0.00000	1	0.16000

35	25	27	0.10930	0.20870	0.00000	1	0.16000
36	28	27	0.00000	0.36900	0.00000	0.95810	0.65000
37	27	29	0.21980	0.41530	0.00000	1	0.16000
38	27	30	0.32020	0.60270	0.00000	1	0.16000
39	29	30	0.23990	0.45330	0.00000	1	0.16000
40	8	28	0.06360	0.20000	0.02140	1	0.32000
41	6	28	0.01690	0.05990	0.00650	1	0.32000

Table A-2: Bus Data

Bus No.	Bus code	Voltage magnitude	Angle(in degrees)	Load (MW)	Load (Mvar)	Gen. (MW)	Gen. (Mvar)	Gen. (Qmin)	Gen. (Qmax)	Inj. Mvar
1	1	1.05	0	0	0	50	-30	0	150	0
2	2	1.033	0	21.7	12.7	20	-30	0	60	0
3	0	1.0	0	2.4	1.2	0	0	0	0	0
4	0	1.0	0	7.6	1.6	0	0	0	0	0
5	2	1.0058	0	94.2	19	15	-15	0	60	0
6	0	1.0	0	0	0	0	0	0	0	0
7	0	1.0	0	22.8	10.9	0	0	0	0	0
8	2	1.023	0	30	30	10	-15	0	50	0
9	0	1.0	0	0	0	0	0	0	0	0
10	0	1.0	0	5.8	2	0	0	0	0	19
11	2	1.0913	0	0	0	10	-10	0	-40	0
12	0	1.0	0	11.2	7.5	0	0	0	0	0
13	2	1.0883	0	0	0	12	-15	0	45	0
14	0	1.0	0	6.2	1.6	0	0	0	0	0
15	0	1.0	0	8.2	2.5	0	0	0	0	0
16	0	1.0	0	3.5	1.8	0	0	0	0	0
17	0	1.0	0	9	5.8	0	0	0	0	0
18	0	1.0	0	3.2	.9	0	0	0	0	0
19	0	1.0	0	9.5	3.4	0	0	0	0	0
20	0	1.0	0	2.2	.7	0	0	0	0	0
21	0	1.0	0	17.5	11.2	0	0	0	0	0
22	0	1.0	0	0	0	0	0	0	0	0
23	0	1.0	0	3.2	1.6	0	0	0	0	0
24	0	1.0	0	8.7	6.7	0	0	0	0	0
25	0	1.0	0	0	0	0	0	0	0	0
26	0	1.0	0	3.5	2.3	0	0	0	0	0

27	0	1.0	0	0	0	0	0	0	0	0
28	0	1.0	0	0	0	0	0	0	0	0
29	0	1.0	0	2.4	.9	0	0	0	0	0
30	0	1.0	0	10.6	1.9	0	0	0	0	0

Table A-3: Cost Coefficients

C	b	a
0	2	.00375
0	1.75	.01750
0	1.00	.06250
0	3.25	.00834
0	3	.02500
0	3	.02500

Table A-4: Generation Limits

MW (Minimum)	MW (Maximum)	Mvar (Minimum)	Mvar (Maximum)
50	200	-30	150
20	80	-30	60
15	50	-15	60
10	35	-15	50
10	30	-10	40
12	40	-15	45

Table A-5: Voltage Limits

V (Min.)	V (Max.)
0	0
0	0
1.2	1.5
1.3	1.6
0	0
1.2	1.4
1.1	1.5
0	0
1.3	1.35

1	1.25
0	0
1.4	1.6
0	0
1.1	1.3
1	1.1
.9	1.2
1.2	1.3
1.3	1.5
1.4	1.6
1.1	1.3
1	1.7
1.3	1.6
1.2	1.4
1.1	1.3
1.4	1.5
1.3	1.5
1.3	1.4
1.2	1.4
1	1.3
1.5	1.6
1.9	1.5

Table A-6: Angle Limits

A (Min.) (in degrees)	A (Max.) (in degrees)
0	0
0	0
-45	45
-45	45
0	0
-45	45
-45	45
0	0
-45	45
-45	45
-45	45
-45	45
0	0

APPENDIX B

Table B-1: Optimal Power Flow Solution without shunt compensation

Maximum Power Mismatch = 0.000404941

No. of Iterations = 2

Bus No.	Voltage magnitude	Angle (degree)	Load (MW)	Load (Mvar)	Gen. (MW)	Gen. (Mvar)	Inj. Mvar
1	1.05	0	0	0	189.728	-12.318	0
2	1.033	0	21.7	12.7	45.882	11.391	0
3	1.029	-6.109	2.4	1.2	0	0	0
4	1.024	-7.343	7.6	1.6	0	0	0
5	1.006	0	94.2	19	17.333	26.536	0
6	1.019	-8.55	0	0	0	0	0
7	1.006	-10.013	22.8	10.9	0	0	0
8	1.023	0	30	30	14.706	46.892	0
9	1.019	-10.493	0	0	0	0	0
10	1.022	-12.331	5.8	2	0	0	19
11	1.031	-8.941	0	0	13.686	6.384	0
12	1.040	-11.704	11.2	7.5	0	0	0
13	1.088	0	0	0	12.769	37.592	0
14	1.025	-12.533	6.2	1.6	0	0	0
15	1.019	-12.705	8.2	2.5	0	0	0
16	1.025	-12.248	3.5	1.8	0	0	0
17	1.017	-12.522	9	5.8	0	0	0
18	1.007	-13.297	3.2	0.9	0	0	0
19	1.004	-13.45	9.5	3.4	0	0	0
20	1.007	-13.229	2.2	0.7	0	0	0
21	1.009	-12.791	17.5	11.2	0	0	0
22	1.01	-12.775	0	0	0	0	0
23	1.007	-13.051	3.2	1.6	0	0	0
24	0.999	-13.154	8.7	6.7	0	0	0
25	1.011	-13.069	0	0	0	0	0
26	0.993	-13.494	3.5	2.3	0	0	0
27	1.027	-12.737	0	0	0	0	0
28	1.014	-9.09	0	0	0	0	0
29	1.007	-13.959	2.4	0.9	0	0	0
30	0.995	-14.836	10.6	1.9	0	0	0
Total Losses			283.4	126.2	294.105	116.477	19

Table B-2: Line Flow and Losses without Shunt Compensation

Line		Power at Line Flow			Line Losses		Transformer Tap
From	To	MW	Mvar	MVA	MW	Mvar	
1		189.728	-12.318	190.127			
	2	127.68	-10.013	128.072	2.848	2.801	
	3	62.082	-2.308	62.125	1.58	2.064	
2		24.182	-1.309	24.218			
	1	-124.83	12.813	125.488	2.848	2.801	
	4	34.422	-6.78	35.083	0.645	-1.926	
	5	68.374	-0.435	68.375	2.069	3.678	
	6	46.219	-6.889	46.73	1.176	-0.367	
3		-2.4	-1.2	2.683			
	1	-60.502	4.372	60.66	1.58	2.064	
	4	58.102	-5.572	58.369	0.424	0.332	
4		-7.6	-1.6	7.767			
	2	-33.777	4.854	34.124	0.645	-1.926	
	3	-57.678	5.904	57.979	0.424	0.332	
	6	52.622	-2.018	52.661	0.315	0.156	
	12	31.232	-10.34	32.9	0	2.712	1.013
5		-76.867	7.536	77.235			
	2	-66.304	4.114	66.432	2.069	3.678	
	7	-10.562	3.425	11.104	0.06	-1.913	
6		0	0	0			
	2	-45.043	6.522	45.513	1.176	-0.367	
	4	-52.308	2.174	52.353	0.315	0.156	
	7	33.723	4.745	34.055	0.301	-0.818	
	8	17.045	-15.837	23.266	0.061	-0.725	
	9	16.66	-7.291	18.186	0	0.684	
	10	12.818	7.343	14.772	0	1.084	
	28	17.105	2.344	17.265	0.049	-1.169	
7		-22.8	-10.9	25.272			
	5	10.622	-5.337	11.888	0.06	-1.913	
	6	-33.422	-5.563	33.882	0.301	-0.818	
8		-15.294	16.892	22.787			
	6	-16.984	15.112	22.734	0.061	-0.725	
	28	1.69	1.794	2.464	0.012	-4.404	
9		0	0	0			
	6	-16.66	7.975	18.47	0	0.684	
	11	-13.686	-5.942	14.921	0	0.446	

	10	30.346	-2.033	30.414	0	0.98	
10		-5.8	17	17.962			
	6	-12.818	-6.259	14.264	0	1.084	
	9	-30.346	3.013	30.496	0	0.98	
	20	9.038	2.949	9.507	0.081	0.181	
	17	5.352	3.29	6.283	0.012	0.032	
	21	15.527	9.645	18.279	0.111	0.24	
	22	7.447	4.362	8.63	0.052	0.107	
11		13.686	6.384	15.102			
	9	13.686	6.388	15.104	0	0.446	
12		-11.2	-7.5	13.479			
	4	-31.232	13.052	33.85	0	2.712	
	13	-12.769	-35.74	37.952	0	1.864	
	14	7.291	2.634	7.753	0.068	0.142	
	15	18.271	8.04	19.961	0.244	0.48	
	16	7.239	4.513	8.531	0.064	0.134	
13		12.769	37.592	39.701			
	12	12.769	37.604	39.713	0	1.864	
14		-6.2	-1.6	6.403			
	12	-7.223	-2.492	7.641	0.068	0.142	
	15	1.023	0.892	1.357	0.004	0.009	
15		-8.2	-2.5	8.573			
	12	-18.027	-7.56	19.548	0.244	0.48	
	14	-1.019	-0.883	1.349	0.004	0.009	
	18	6.009	2.365	6.458	0.043	0.088	
	23	4.837	3.578	6.017	0.035	0.07	
16		-3.5	-1.8	3.936			
	12	-7.176	-4.379	8.406	0.064	0.134	
	17	3.676	2.579	4.49	0.016	0.037	
17		-9	-5.8	10.707			
	16	-3.66	-2.542	4.456	0.016	0.037	
	10	-5.34	-3.258	6.255	0.012	0.032	
18		-3.2	-0.9	3.324			
	15	-5.966	-2.277	6.386	0.043	0.088	
	19	2.766	1.377	3.09	0.006	0.012	
19		-9.5	-3.4	10.09			
	18	-2.76	-1.365	3.079	0.006	0.012	
	20	-6.74	-2.035	7.041	0.017	0.033	
20		-2.2	-0.7	2.309			

	19	6.757	2.068	7.066	0.017	0.033	
	10	-8.957	-2.768	9.375	0.081	0.181	
21		-17.5	-11.2	20.777			
	10	-15.416	-9.405	18.058	0.111	0.24	
	22	-2.084	-1.795	2.75	0.001	0.002	
22		0	0	0			
	10	-7.395	-4.255	8.531	0.052	0.107	
	21	2.085	1.796	2.752	0.001	0.002	
	24	5.31	2.458	5.851	0.039	0.06	
23		-3.2	-1.6	3.578			
	15	-4.802	-3.508	5.947	0.035	0.07	
	24	1.602	1.908	2.491	0.008	0.017	
24		-8.7	-6.7	10.981			
	22	-5.271	-2.398	5.791	0.039	0.06	
	23	-1.594	-1.891	2.473	0.008	0.017	
	25	-1.835	-2.41	3.03	0.017	0.03	
25		0	0	0			
	24	1.853	2.441	3.064	0.017	0.03	
	26	3.545	2.368	4.263	0.045	0.068	
	27	-5.398	-4.808	7.229	0.056	0.107	
26		-3.5	-2.3	4.188			
	25	-3.5	-2.3	4.188	0.045	0.068	
27		0	0	0			
	25	5.454	4.915	7.342	0.056	0.107	
	28	-18.734	-8.243	20.467	0	1.467	
	29	6.189	1.667	6.41	0.086	0.162	
	30	7.091	1.661	7.283	0.161	0.303	
28		0	0	0			
	27	18.734	9.71	21.101	0	1.467	0.958
	8	-1.678	-6.197	6.42	0.012	-4.404	
	6	-17.056	-3.513	17.414	0.049	-1.169	
29		-2.4	-0.9	2.563			
	27	-6.103	-1.505	6.286	0.086	0.162	
	30	3.703	0.605	3.753	0.033	0.063	
30		-10.6	-1.9	10.769			
	27	-6.93	-1.358	7.062	0.161	0.303	
	29	-3.67	-0.542	3.71	0.033	0.063	
Total Losses					10.738	9.325	

Table B-3: Optimal Power Flow Solution with Shunt CompensationValue of $Y_c=0.066$ ohms

Bus no. =12

Bus No.	Voltage magnitude	Angle	Load	Load (Mvar)	Gen. (MW)	Gen. (Mvar)	Inj. Mvar
		(in degrees)	(MW)				
1	1.05	0	0	0	189.765	-12.69	0
2	1.033	0	21.7	12.7	45.882	10.649	0
3	1.03	-6.12	2.4	1.2	0	0	0
4	1.025	-7.356	7.6	1.6	0	0	0
5	1.006	0	94.2	19	17.333	26.296	0
6	1.019	-8.551	0	0	0	0	0
7	1.006	-10.011	22.8	10.9	0	0	0
8	1.023	0	30	30	14.706	45.515	0
9	1.02	-10.477	0	0	0	0	0
10	1.024	-12.302	5.8	2	0	0	19
11	1.031	-8.926	0	0	13.686	5.801	0
12	1.045	-11.732	11.2	7.5	0	0	0
13	1.088	0	0	0	12.769	33.403	0
14	1.03	-12.548	6.2	1.6	0	0	0
15	1.023	-12.711	8.2	2.5	0	0	0
16	1.029	-12.247	3.5	1.8	0	0	0
17	1.02	-12.499	9	5.8	0	0	0
18	1.011	-13.286	3.2	0.9	0	0	0
19	1.007	-13.429	9.5	3.4	0	0	0
20	1.01	-13.206	2.2	0.7	0	0	0
21	1.011	-12.762	17.5	11.2	0	0	0
22	1.012	-12.746	0	0	0	0	0
23	1.01	-13.044	3.2	1.6	0	0	0
24	1.002	-13.134	8.7	6.7	0	0	0
25	1.013	-13.044	0	0	0	0	0
26	0.995	-13.468	3.5	2.3	0	0	0
27	1.028	-12.711	0	0	0	0	0
28	1.015	-9.088	0	0	0	0	0
29	1.008	-13.93	2.4	0.9	0	0	0
30	0.997	-14.804	10.6	1.9	0	0	0
Total			283.4	126.2	294.141	108.975	19

Table B-4: Line Flow and Losses with Shunt Compensation

Line		Power at Line Flow			Line Losses		Transformer Tap
From	To	MW	Mvar	MVA	MW	Mvar	
1		189.765	-12.69	190.189			
	2	127.628	-9.999	128.019	2.845	2.794	
	3	62.14	-2.689	62.198	1.583	2.074	
2		24.182	-2.051	24.269			
	1	-124.78	12.793	125.436	2.845	2.794	
	4	34.449	-7.263	35.206	0.649	-1.918	
	5	68.335	-0.43	68.336	2.067	3.669	
	6	46.181	-7.147	46.731	1.176	-0.37	
3		-2.4	-1.2	2.683			
	1	-60.557	4.763	60.744	1.583	2.074	
	4	58.157	-5.963	58.462	0.425	0.333	
4		-7.6	-1.6	7.767			
	2	-33.8	5.344	34.22	0.649	-1.918	
	3	-57.732	6.296	58.074	0.425	0.333	
	6	52.412	-1.099	52.423	0.311	0.143	
	12	31.52	-12.141	33.778	0	2.854	1.013
5		-76.867	7.296	77.212			
	2	-66.268	4.099	66.394	2.067	3.669	
	7	-10.599	3.198	11.071	0.059	-1.915	
6		0	0	0			
	2	-45.006	6.776	45.513	1.176	-0.37	
	4	-52.1	1.243	52.115	0.311	0.143	
	7	33.76	4.972	34.124	0.302	-0.816	
	8	17.016	-14.706	22.491	0.057	-0.739	
	9	16.543	-7.645	18.224	0	0.686	1.016
	10	12.75	7.02	14.555	0	1.051	0.963
	28	17.037	2.34	17.197	0.049	-1.171	
7		-22.8	-10.9	25.272			
	5	10.658	-5.112	11.821	0.059	-1.915	
	6	-33.458	-5.788	33.955	0.302	-0.816	
8		-15.294	15.515	21.786			
	6	-16.959	13.967	21.97	0.057	-0.739	
	28	1.665	1.556	2.279	0.01	-4.409	
9		0	0	0			
	6	-16.543	8.331	18.523	0	0.686	

	11	-13.686	-5.372	14.703	0	0.432	
	10	30.229	-2.959	30.374	0	0.975	
10		-5.8	17	17.962			
	6	-12.75	-5.969	14.078	0	1.051	
	9	-30.229	3.934	30.484	0	0.975	
	20	8.964	2.585	9.33	0.078	0.174	
	17	5.257	2.626	5.876	0.011	0.028	
	21	15.518	9.534	18.213	0.11	0.237	
	22	7.44	4.29	8.588	0.051	0.106	
11		13.686	5.801	14.865			
	9	13.686	5.805	14.866	0	0.432	
12		-11.2	-7.5	13.479			
	4	-31.52	14.995	34.905	0	2.854	
	13	-12.769	-31.912	34.372	0	1.513	
	14	7.315	2.749	7.815	0.069	0.143	
	15	18.43	8.687	20.375	0.251	0.495	
	16	7.343	5.195	8.995	0.07	0.147	
13	0	12.769	33.403	35.761			
	12	12.769	33.426	35.781	0	1.513	
14		-6.2	-1.6	6.403			
	12	-7.247	-2.606	7.701	0.069	0.143	
	15	1.047	1.006	1.452	0.004	0.01	
15		-8.2	-2.5	8.573			
	12	-18.179	-8.192	19.939	0.251	0.495	
	14	-1.042	-0.996	1.441	0.004	0.01	
	18	6.081	2.727	6.665	0.045	0.093	
	23	4.939	3.961	6.332	0.038	0.077	
16		-3.5	-1.8	3.936			
	12	-7.273	-5.047	8.853	0.07	0.147	
	17	3.773	3.247	4.978	0.019	0.045	
17		-9	-5.8	10.707			
	16	-3.754	-3.202	4.934	0.019	0.045	
	10	-5.246	-2.598	5.854	0.011	0.028	
18		-3.2	-0.9	3.324			
	15	-6.036	-2.634	6.586	0.045	0.093	
	19	2.836	1.734	3.324	0.007	0.014	
19		-9.5	-3.4	10.09			
	18	-2.829	-1.72	3.311	0.007	0.014	
	20	-6.671	-1.68	6.879	0.016	0.032	

20		-2.2	-0.7	2.309			
	19	6.687	1.712	6.902	0.016	0.032	
	10	-8.887	-2.412	9.208	0.078	0.174	
21		-17.5	-11.2	20.777			
	10	-15.408	-9.297	17.995	0.11	0.237	
	22	-2.092	-1.903	2.828	0.001	0.002	
22		0	0	0			
	10	-7.389	-4.184	8.491	0.051	0.106	
	21	2.093	1.905	2.83	0.001	0.002	
	24	5.295	2.279	5.765	0.037	0.058	
23		-3.2	-1.6	3.578			
	15	-4.901	-3.884	6.253	0.038	0.077	
	24	1.701	2.284	2.848	0.01	0.021	
24		-8.7	-6.7	10.981			
	22	-5.258	-2.221	5.708	0.037	0.058	
	23	-1.691	-2.262	2.824	0.01	0.021	
	25	-1.751	-2.217	2.825	0.015	0.026	
25		0	0	0			
	24	1.766	2.243	2.855	0.015	0.026	
	26	3.545	2.367	4.263	0.045	0.067	
	27	-5.311	-4.61	7.033	0.053	0.101	
26		-3.5	-2.3	4.188			
	25	-3.5	-2.3	4.188	0.045	0.067	
27		0	0	0			
	25	5.364	4.711	7.139	0.053	0.101	
	28	-18.643	-8.037	20.302	0	1.439	
	29	6.189	1.667	6.409	0.085	0.161	
	30	7.091	1.66	7.282	0.161	0.302	
28		0	0	0			
	27	18.643	9.477	20.914	0	1.439	0.958
	8	-1.655	-5.965	6.19	0.01	-4.409	
	6	-16.988	-3.512	17.348	0.049	-1.171	
29		-2.4	-0.9	2.563			
	27	-6.103	-1.505	6.286	0.085	0.161	
	30	3.703	0.605	3.752	0.033	0.063	
30		-10.6	-1.9	10.769			
	27	-6.93	-1.358	7.062	0.161	0.302	
	29	-3.67	-0.542	3.71	0.033	0.063	
Total Losses					10.744	9.029	

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